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Design & Analysis of Composite Cylinder for Aerospace Applications

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ABSTRACT

This thesis work is devoted to design Submarine Launch Cruise Missile Composite cylinders to meet the stipulated external pressure under operating conditions with adequate factor of safety. The design geometry of the Composite cylinder comprising various metallic parts and composite cylinder is to be obtained after giving it a thorough analytical and theoretical treatment. The designed configurations have to be backed up by finite element analysis results.

The Composite cylinder has to be designed so as to sustain the stipulated external pressure. The layered analysis of filament wound composite cylinder will be carried out. The procedure followed has worked out to be efficient in accurately predicting the structural response of composite components in the past. The design stresses are to be within safe limits. It has to meet all the desired functional requirements.

1. INTRODUCTION

1.1 COMPOSITE MATERIALS

A typical composite material is a system of materials composing of two or more materials (mixed and bonded) on a macroscopic scale. For example, concrete is made up of cement, sand, stones, and water. If the composition occurs on a microscopic scale (molecular level), the new material is then called an alloy for metals or a polymer for plastics. Generally, a composite material is composed of reinforcement (fibers, particles, flakes, and/or fillers) embedded in a matrix (polymers, metals, or ceramics). The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix. When designed properly, the new combined material exhibits better strength than would each individual material.

1.2 COMMON CATEGORIES OF COMPOSITE MATERIALS

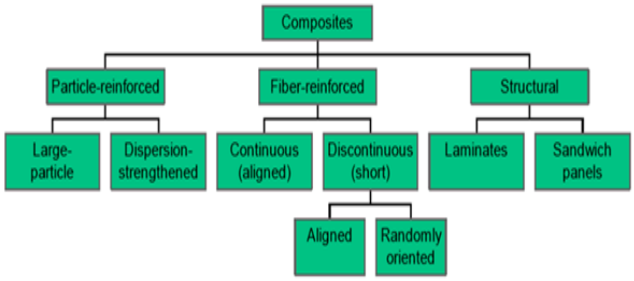

Fig 1.1: Classification of Composite Materials

1.3 TYPES OF MATRIX

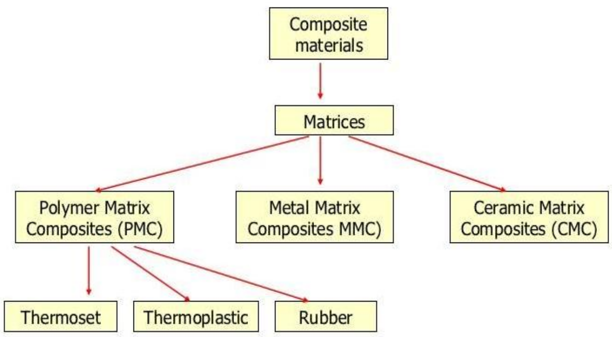

Fig1.2: Polymer Matrix Composites (PMC)

The main disadvantages of Polymer Matrix Composites (PMC) are:

- Low thermal resistance;
- High coefficient of thermal expansion.

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2. LITERATURE SURVEY

The buckling of the orthotropic shells was also a subject of interest since the 1960s. However, the formulations developed, to date, require numerical solutions to obtain the critical pressure. In this work, the generalized closed from analytical formulae for the buckling of thin orthotropic multi-angle laminated long cylinders is developed. Standard energy based formulation is used to express the kinematics and equilibrium equations. Classical laminatetheory is implemented to introduce the constitutive equations of thin shells. These equations are statically condensed, in terms of the ring's boundary conditions, to produce effective axial, coupling and flexural rigidities for the cases of ring and long cylinders. The critical buckling pressure may be calculated by hand using the derived equation in terms of these effective elastic rigidities.

The main objectives of the thesis

- To reduce the weight of composite shell for better performance
- Design of composite shell based on axial loading and column buckling
- Minimizing the cost of Shell
- FE analysis and optimization of composite shell and Experimental validation of design methodology.

3. DESIGN

The stiffness matrix of the composite tube is calculated for various orientations according to the Classical Laminate Theory for various orientations.
The derivations of CLT is as follows:

Assume that the shell is stiffened by closely spaced circular circumferential rings. According to the above theory, first replace the given naturally orthotropic and stiffened circular shell by a structurally orthotropic shell having the extensional and flexural rigidities. Inserting the expressions of stress,the following stress resultants–displacement relations

$$N_1 = B_{11}\frac{du}{dx} - B_{12}\frac{w}{R} - K_{11}\frac{d^2w}{dx^2}; \qquad N_2 = -B_{22}\frac{w}{R} + B_{21}\frac{du}{dx};$$

$$M_1 = -D_{11}\frac{d^2w}{dx^2} + K_{11}\frac{du}{dx} \tag{3.1}$$

Using the first Eq. (3.1), express du=dx in terms of N1and w, and then substitute the result into the second and third Eq. We obtain the following:

$$N_2 = \frac{1}{B_{11}}\left[B_{21}N_1 + \frac{w}{R}(B_{21}^2 - B_{22}B_{11}) + B_{21}K_{11}\frac{d^2w}{dx^2}\right]$$

$$M_1 = \frac{1}{B_{11}}\left[K_{11}N_1 + \frac{w}{R}K_{11}B_{12} + (K_{11}^2 - B_{11}D_{11})\frac{d^2w}{dx^2}\right] \tag{3.2}$$

Inserting the above equations into the equilibrium equation results in the following governing differential equation for an axisymmetrically loaded, structurally orthotropic circular cylindrical shell (stiffened by circumferential rings):

$$\frac{d^4w}{dx^4} - 2\lambda^2\frac{d^2w}{dx^2} + 4\beta_s^4 w = f(p_3, N_1) \tag{3.3}$$

Where

$$\lambda^2 = \frac{K_{11}B_{12}}{2RD_s}; \beta_s^4 = \frac{B_s}{4D_sR^2}; D_s = B_{11}D_{11} - K_{11}^2; B_s = B_{11}B_{22} - B_{12}^2;$$

$$f(p_3, N_1) = \frac{1}{D_s}\left(B_{11}p_3 + K_{11}\frac{d^2N_1}{dx^2} + \frac{B_{21}}{R}N_1\right) \tag{3.4}$$

The membrane meridional force N1 may be found i.e.,

$$N_1 = -\int p_1 dx + N_1^{(0)} \tag{3.5}$$

where$N_1^{(0)}$is the meridional force in a reference section of the shell, x= 0.For an unstiffened, isotropic, circular cylindrical shell, axisymmetrically loaded by a pressure p3, one obtains the following:

$$K_{11} = 0, B_{11} = B_{22} = B, B_{21} = \nu B; B_s = B^2(1-\nu^2),$$

$$D_{11} = D = \frac{Eh^3}{12(1-\nu^2)}, \lambda = 0, \beta_s^4 = \beta^4$$

$$D_s = BD, f(p_3, N_1) = \frac{1}{BD}\left(p_3 + \frac{\nu B}{R}N_1\right) \tag{3.6}$$

and Eqs (3.6) will be reduced for an isotropic circular cylindrical shell loaded axisymmetrically by a pressure p_3(if $p_1 = 0$then $N_1 =$ const, and $\frac{d^2N_1}{dx^2} = 0$).

Lamina stress-strain behaviour

The stress-strain relations in principal material coordinates for a lamina of an orthotropic material under plane stress .The reduced stiffnesses, Qij are defined in terms of the engineering constants. In any other coordinate system in the plane of the lamina, the stresses are

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\end{bmatrix} = \begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{12} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \epsilon_2\\ \varepsilon_3\end{bmatrix} \tag{3.7}$$

Resultant laminate forces and moments

The resultant forces and moments acting on a laminate are obtained by integration of the stresses in each layer or lamina through the laminate thickness, for example,

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$$N_X = \int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma_x \, dz$$

$$M_X = \int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma_X \, dZ \qquad (3.8)$$

$$\begin{bmatrix} N_X \\ N_Y \\ N_{XY} \end{bmatrix} = \int_{-t/2}^{t/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dZ = \sum_{K=1}^{N} \int_{Z_{(K-1)}}^{Z_K} \begin{bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{bmatrix}_K dZ$$

And

$$\begin{bmatrix} M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \int_{-\frac{t}{2}}^{\frac{t}{2}} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} Z dZ = \sum_{K=1}^{N} \int_{Z_{(K-1)}}^{Z_K} \begin{bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{bmatrix}_K dZ \qquad (3.9)$$

Thus, Equations (3.8)and (3.9)can be written as

$$\begin{bmatrix} N_X \\ N_Y \\ N_{XY} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \gamma_{XY} \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{26} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} K_X \\ K_Y \\ K_{XY} \end{bmatrix}$$

$$\begin{bmatrix} M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \gamma_{XY} \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{26} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} K_X \\ K_Y \\ K_{XY} \end{bmatrix} \qquad (3.10)$$

Where

$$A_{ij} = \sum_{K=1}^{N} (\bar{Q}_{ij})_k (z_k - z_{k-1})$$

$$B_{ij} = \frac{1}{2} \sum_{K=1}^{N} (\bar{Q}_{ij})_k (Z^2{}_k - Z^2{}_{k-1})$$

$$D_{ij} = \frac{1}{3} \sum_{K=1}^{N} (\bar{Q}_{ij})_k (Z^3{}_k - Z^3{}_{k-1}) \qquad (3.11)$$

The extensional and the bending stiffnesses are calculated from equation (3.11) wherein for the k^{th} layer

$$\overline{(Q_{11})}\_k = \frac{E_1}{1 - \nu_{21}\nu_{21}}$$

$$(\bar{Q}_{12})_k = \frac{E_1 \nu_{12} \nu_{21}}{1 - \nu_{12}\nu_{21}}$$

$$\overline{(Q_{22})}\_K = \frac{E_2}{1 - \nu_{21}\nu_{12}}$$

$$(\bar{Q}_{16}) = (\bar{Q}_{26}) = 0$$

$$(\bar{Q}_{66}) = G_{12} \qquad (3.12)$$

Or, in terms of engineering constants,

$$Q_{11} = \frac{E_1}{1 - \nu_{12}\nu_{21}} \qquad Q_{22} = \frac{E_2}{1 - \nu_{21}\nu_{12}}$$

$$Q_{12} = \frac{\nu_{12} E_2}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{21} E_1}{1 - \nu_{12}\nu_{21}} \qquad Q_{66} = G_{12} \qquad (3.13)$$

Stress-Strain Relations for A Lamina Of Arbitrary Orientation

stresses in a 1-2 coordinate system,

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta \\ \sin\theta\cos\theta & -\sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \qquad (3.14)$$

the strain-transformation equations are

$$\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \frac{\gamma_{xy}}{2} \end{bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta \\ \sin\theta\cos\theta & -\sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \frac{\gamma_{12}}{2} \end{bmatrix} \qquad (3.15)$$

A so-called specially orthotropic lamina is an orthotropic lamina whose principle material axes are aligned with the natural body axes

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{bmatrix} \qquad (3.16)$$

The stress-strain relations in x-y coordinates are

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [\bar{Q}] \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} \qquad (3.17)$$

In which

$$\overline{Q_{11}} = Q_{11}\cos^4\theta + 2(Q_{12} + Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\sin^4\theta$$

$$\overline{Q_{12}} = (Q_{11} + Q_{22} - 4Q_{66})\sin^2\theta\cos^2\theta + Q_{12}(\sin^4\theta + \cos^4\theta)$$

$$\overline{Q_{22}} = Q_{11}\sin^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta$$

$$\overline{Q_{16}} = (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin^3\theta\cos\theta$$

$$\overline{Q_{26}} = (Q_{11} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin\theta\cos^3\theta$$

$$\overline{Q_{66}} = Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + Q_{66}(\sin^4\theta + \cos^4\theta) \qquad (3.18)$$

Transformation of the stress-strain relations in principle material coordinates

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \qquad (3.19)$$

To body coordinates. We choose the second approach and apply the transformations of equation 2.74 and 2.75 along with Reuter's matrix, equation (3.19), to obtain

$$\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} = [T]^T[S][T] \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \overline{S_{11}} & \overline{S_{12}} & \overline{S_{16}} \\ \overline{S_{12}} & \overline{S_{22}} & \overline{S_{26}} \\ \overline{S_{16}} & \overline{S_{26}} & \overline{S_{66}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \qquad (3.20)$$

Where

$$\overline{S_{11}} = S_{11}\cos^4\theta + (2S_{12} + S_{66})\sin^2\theta\cos^2\theta + S_{22}\sin^4\theta$$

$$\overline{S_{12}} = S_{12}(\sin^4\theta + \cos^4\theta) + (S_{11} + S_{22} - S_{66})\sin^2\theta\cos^2\theta$$

$$\overline{S_{22}} = S_{11}\sin^4\theta + (2S_{12} + S_{66})\sin^2\theta\cos^2\theta + S_{22}\cos^4\theta$$

$$\overline{S_{16}} = (2S_{11} - 2S_{12} - S_{66})\sin\theta\cos^3\theta - (2S_{22} - 2S_{12} - S_{66})\sin^3\theta\cos\theta$$

$$\overline{S_{26}} = (2S_{11} - 2S_{12} - S_{66})\sin^3\theta\cos\theta - (2S_{22} - 2S_{12} - S_{66}\sin\theta\cos^3\theta)$$

$$\overline{S_{66}} = 2(2S_{11} + 2S_{22} - 4S_{12} - S_{66})\sin^2\theta\cos^2\theta + S_{66}(\sin^4\theta + \cos^4\theta) \qquad (3.21)$$

Or inverted form as

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{16} \\ S_{12} & S_{22} & S_{26} \\ S_{16} & S_{26} & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \qquad (3.22)$$

The results for various ply orientations is given below:

PLY ORIENTATION →	90 +10 -10 90	90 +30 -30 +90	90 +45 -45 90	90 +70 -70 90	90 +85 -85 90
MODULUS $[E_2]$	95753.26495	**97270.71997**	114752.4135	142468.635	158831.1435
THICKNESS [t]	1.608745466	**2.05296488**	2.054694765	1.807739339	1.74339987

TABLE 3.1:Thickness Calculations For Different Ply-Orientations

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Material Properties OfTowpreg-

Stiffness			
E_1	140,000	MPa	Young's modulus along fiber
E_2	9000	MPa	Young's modulus across fiber
G_{12}	4500	MPa	In-plane shear modulus
υ_{12}	0.25	-	Poisson's ratio
υ_{23}	0.32	-	Poisson's ratio
ρ	1500	Kg/m^3	Density of composite
Strength			
$\sigma_1^{tension}$	2000	MPa	Tension strength
$\sigma_1^{compression}$	850	MPa	Compressive strength
$\sigma_2^{tension}$	34	MPa	Tension strength
$\sigma_2^{compression}$	210	MPa	Compressive strength
τ_{12}	80	MPa	In-plane shear strength
τ_{23}	80	MPa	Out-of-plane shear strength

TABLE 3.2: Material Properties

The final component are given in Fig.3.3

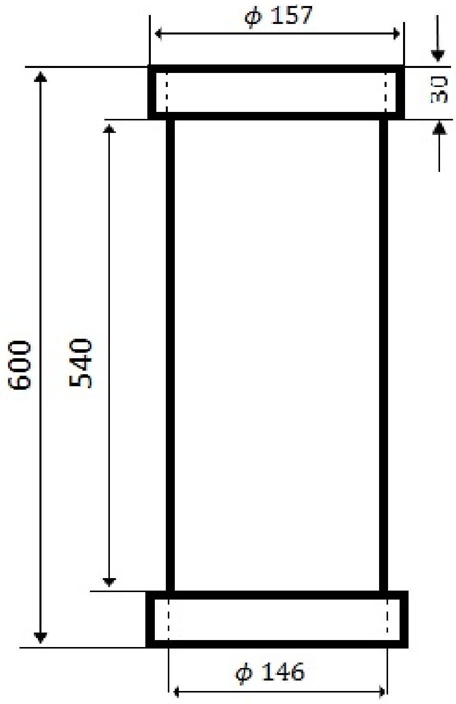

Fig.3.1 Composite Shell

4. ANALYSIS

The structural analysis is performed in ANSYS Mechanical APDL and results are as follows:

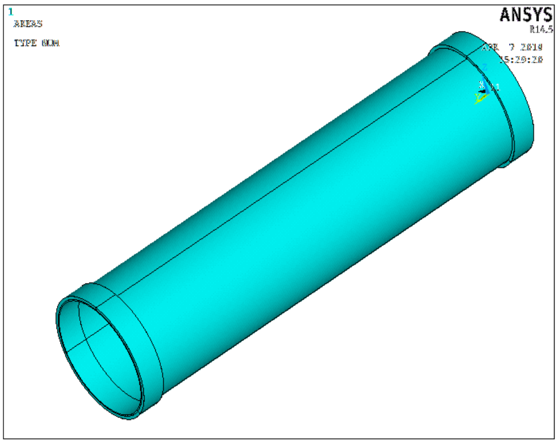

Fig 4.1: Model

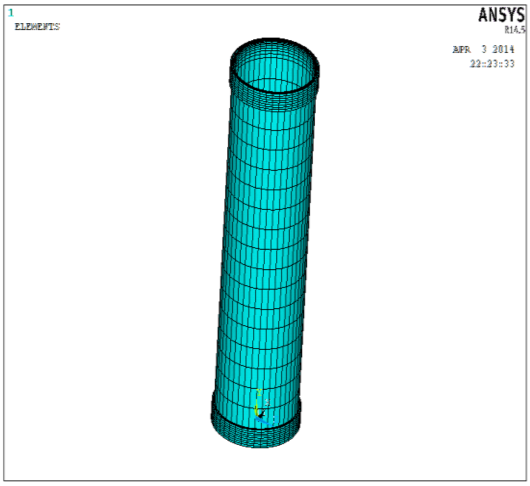

Fig 4.2: Meshing

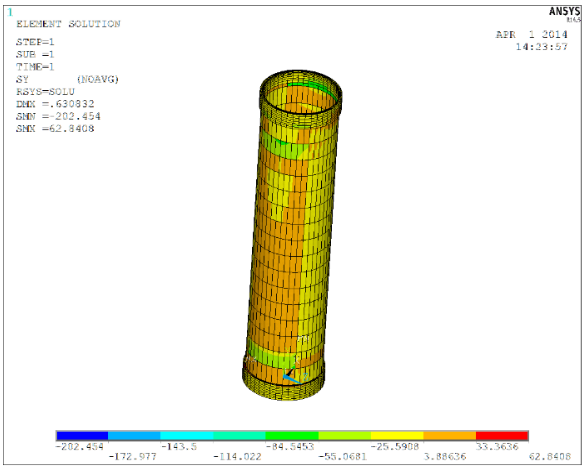

Fig 4.3: Hoop Stress

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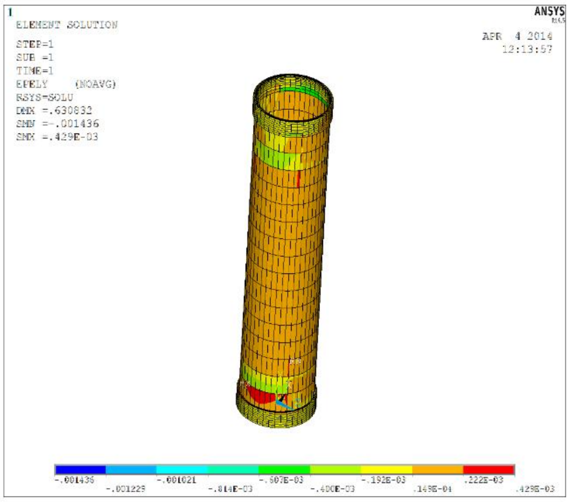

Fig 4.4: Hoop Strain

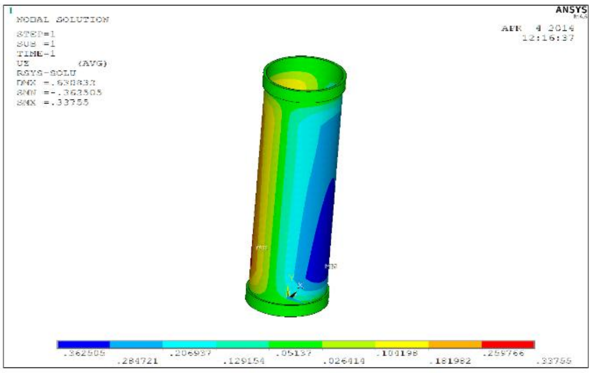

Fig 4.5: Axial Displacement

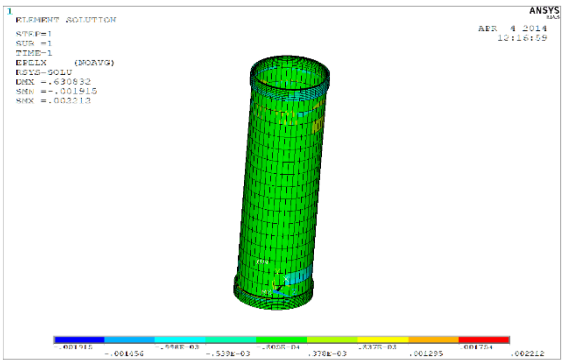

Fig 4.6: Radial Strain

S.NO	DESCRIPTION	DMX	SMN	SMX
1.	Radial Displacement	0.630832	0.008879	0.107456
2.	Hoop Stress	0.630832	-202.454	62.8408
3.	Hoop strain	0.630832	0.001436	0.422e-03
4.	Axial Strain	0.630832	0.005765	0.002034
5.	Axial Stress	0.630832	-33.7324	12.2039
6.	Axial Displacement	0.630832	0.362505	0.33755
7.	Radial strain	0.630832	0.001915	0.002212

TABLE 4.1: Analysis Summary

5.MANUFACTURING

The process used in manufacturing of the composite cylinder is filament winding. In a filament winding process, a band of continuous resin impregnated roving's or monofilaments is wrapped around a rotating mandrel and then cured either at room temperature or in an oven to produce the final product. The mandrel can be cylindrical, round or any shape that does not have re-entrant curvature. Modern winding machines are numerically controlled with higher degrees freedom or laying exact number of layers of reinforcement. Mechanical strength of the filament wound parts not only depend on composition of component material but also on process parameters like winding angle, fiber tension, resin chemistry and curing cycle. Fibers can either be use dry or be pulled through a resin batch before being wound onto the mandrel. The winding pattern is controlled by the rotational speed of the mandrel and the movement of the fiber feeding mechanism.

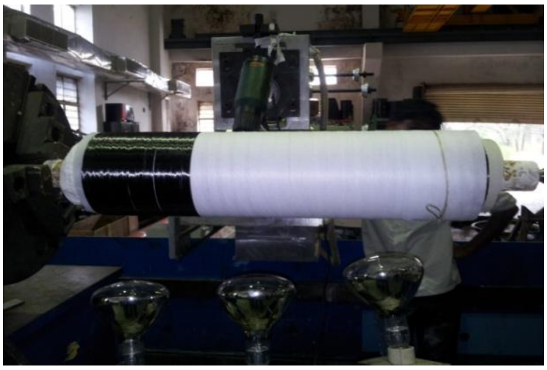

Fig 5.1: Hoop Winding

Fig5.2: Final Component

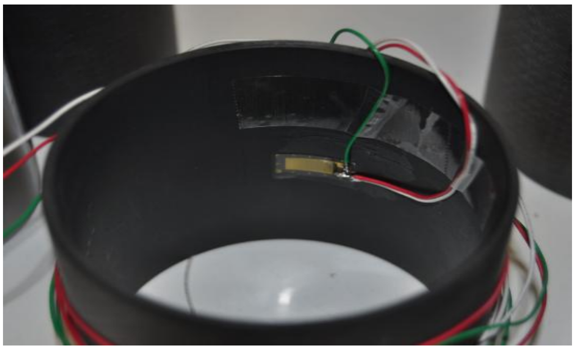

Fig 5.3:strain gage arrangement

Fig 5.4:Composite shell with end bungs

6.EXPERIMENTAL TESTING AND VALIDATION

6.1 TESTING OF THE COMPOSITE CYLINDER

The composite stiffened shell is assembled to test cylinder. The main objective of the testing are

- To measure the strains at specified load levels which in turn give corresponding stress/ strength levels.
- To measure the dilations / deformations of shell at various locations due to applied load.

6.2 TEST SETUP

The test setup is as shown in Fig.6.1 the cylinder is tested with external pressure. The test article was put in position and holding fixture. All strain gauges were connected to strain data acquisition system (DAS) All specified locations LVDT’s were mounted to measure the dilations. The shell was buckled at 22.3 bar external pressure. Based on the test results, the achieved buckling factor is 3.71. Based on this, design of composite cylinder is safe and failed shell is given in Fig 6.2

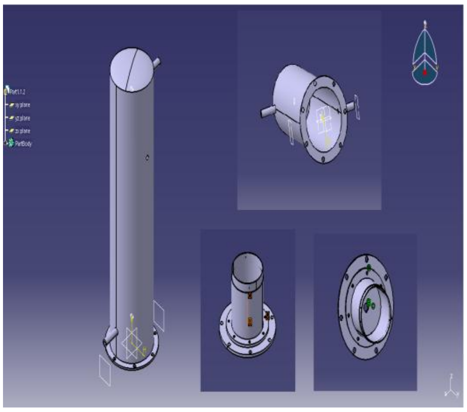

Fig 6.1Test setup

Fig 6.2Failed shell

7. CONCLUSION

7.1 The Submarine Launch Cruise Missile Composite cylinder is designed to meet the stipulated external pressure under operating conditions with adequate factor of safety. The design geometry of the Composite cylinder comprising various metallic parts and composite cylinder is obtained after giving it a thorough analytical and theoretical treatment. The designed configurations have been backed up by finite element analysis results.

7.2 Based on the analysis the following conclusions have been drawn:

1. The Composite cylinder designed is meeting the stipulated external pressure. The layered analysis of filament wound composite cylinder is carried out. The procedure followed has worked out to be efficient in accurately predicting the structural response of composite components in the past.
2. The design stresses are within safe limits.

3. It meets all the desired functional requirements.

7.3 In future work, we need to carry out the FE analysis of cylinder with end plate to simulate the actual conditions.

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